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An Intensity-Based Demodulation Approach for the Measurement of Strains Induced by Structural Vibrations using Bragg Gratings

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ABSTRACT

The Structural Irregularity and Damage Evaluation Routine (SIDER) is a broadband vibration-based technique that uses features in the complex curvature operating shapes of vibrating structures to locate damage and other areas with structural stiffness variations.

Historically SIDER has determined these shapes using out-of-plane acceleration measurements, however it may also be possible to determine these complex curvature operating shapes by using arrays of fibre Bragg gratings to measure the dynamic strain profile of the vibrating structure.

This report outlines a review of commercially available FBG demodulation systems with the requirements of SIDER in mind. Three commercially available systems were assessed in the Laboratory and found to be unsuitable for this study. Hence in order to achieve a suitable outcome a purpose-built demodulation system was developed by DSTO. This report describes the assessment of the commercial systems as well as the development and evaluation of the DSTO purpose-built demodulation system.

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Executive Summary

The work described in this report forms part of an experimental program sponsored by the US Office of Naval Research (ONR) under Grant No. N00014-09-1-0364.

The three year program entitled "Structural Health Monitoring Through Environmental Excitation and Optical Fibre Sensors" commenced in December 2008. It is a collaborative research effort involving researchers from the US Naval Academy (NA), Naval Surface Warfare Center (NSWC), the Australian Co-operative Research Centre for Advanced Composite Structures (CRCACS) and DSTO.

The ultimate goal of the program is the demonstration and validation of a large area vibration-based structural health monitoring system on a composite structure using simulated environmental excitation and a network of surface-mounted fibre Bragg gratings for response measurement.

DSTO's involvement in this program is to develop the distributed Bragg grating interrogation system and conduct studies on the reliability, durability and packaging of the Bragg gratings.

This report outlines a review of commercially available FBG demodulation systems with the requirements of SIDER in mind. Three commercially available systems were assessed in the Laboratory and found to be unsuitable for this study. Hence in order to achieve a suitable outcome a purpose-built demodulation system was developed by DSTO. The assessment of the commercial systems as well as the development and evaluation of the DSTO purpose-built demodulation system is described.

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1 Introduction

The Structural Irregularity and Damage Evaluation Routine (SIDER) is a broadband vibration-based technique that uses features in the complex curvature operating shapes of vibrating structures to locate damage and other areas with structural stiffness variations. SIDER was developed by researchers at the US Naval Surface Warfare Center — Carderock Division (NSWCCD) and the US Naval Academy (USNA) for the inspection of large-scale composite structures which are difficult and time consuming to inspect using conventional inspection methods[1].

The current SIDER methodology utilises impact excitation across a test grid and records the vibrational response using a small number of accelerometers. The test grid excitation approach enables a dense mapping of the operational curvature shapes without the requirement for a large number of sensors which would raise significant engineering issues associated with their weight and wiring. However the requirement for multiple point excitation means that this testing can only be applied when the structure is out of service and the generation of the curvature shapes can take many hours depending on the size of the grid.

Bragg gratings in optical fibres have the potential to overcome some of these engineering challenges. Fibre Bragg gratings (FBGs) are immune to electromagnetic interference, are inherently corrosion-resistant and their size and weight allow them to be incorporated into or onto composite structures with minimal intrusion. The number of sensors that can be written on a single fibre is limited only by the physical length of the gratings (usually a few mm) and the bandwidth of the laser source available for interrogation. The practical benefit of this in terms of sensor networking is obvious. In the particular case of SIDER, the excitation grid can be replaced by a measurement grid, allowing for single point or environmental excitation. The spatially separated measurements of strain can be used to provide the curvature shapes directly. This change in approach could potentially transition SIDER from a routine broad-area inspection tool to an in-service structural health monitoring system.

2 Determination of System Requirements

One of the major challenges associated with this type of distributed response measurement using Bragg gratings is that the strains induced by structural vibrations tend to be low and can often occur at reasonably high frequencies. In addition, the operational loading scenarios may also be expected to induce some higher amplitude pseudo-static strains associated with the manoeuvre loads on the structure. The implications of this are that while the strain range required for vibrational strains may be low, the system must be capable of operating with an underlying higher strain level which limits the application of some of the fixed FBG wavelength demodulation approaches.

In recent years, many commercial off the shelf (COTS) FBG interrogators have come to market but typically, regardless of the demodulation approach, there tends to be a compromise between speed, multiplexing capability and strain resolution.

In order to assess the suitability of the COTS systems to provide a distributed measurement of dynamic strain from a series of FBG arrays it was first necessary to develop the required system specifications, i.e. define the minimum strain resolution and frequency range required to provide a meaningful input for SIDER. These specifications were determined through a series of experimental measurements and by consultation with the developers of the SIDER technique.

The experimental measurements were conducted by exciting a standard e-glass/vinyl ester composite beam with both an instrumented hammer and using random excitation from an electrodynamic shaker. The resultant strains were measured using both an electrical resistance strain gauge and an FBG.

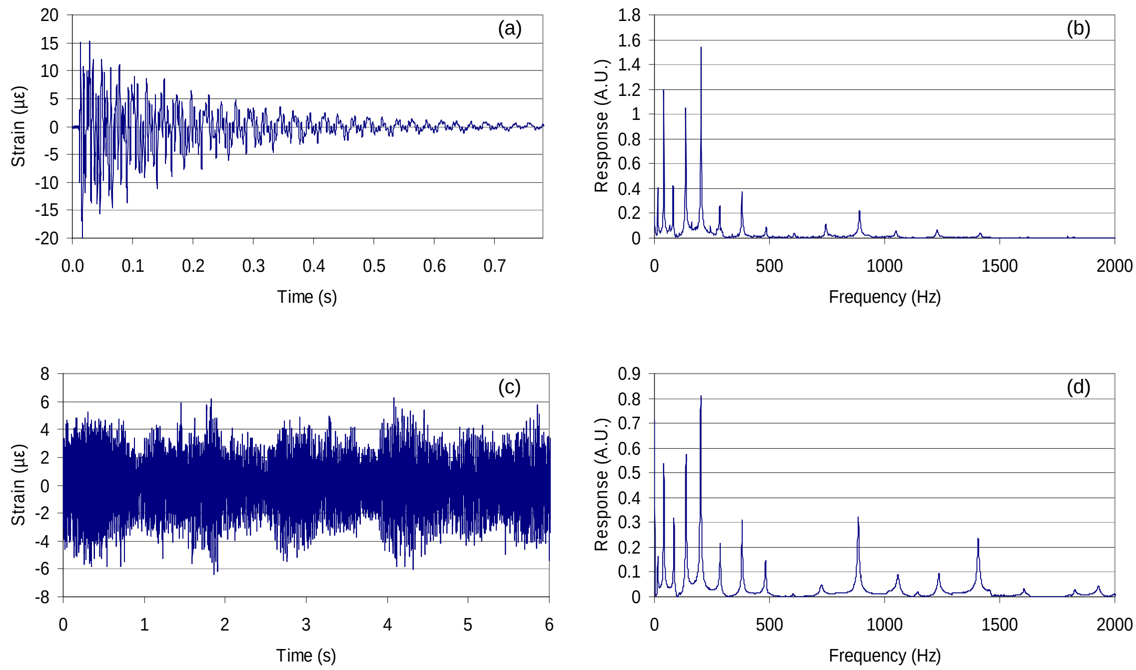


Figure 1: *Excitation strain time history and frequency response function plots for (top) hammer tap and (bottom) shaker excitation*

Figure 1 shows the strain history for both excitation methods along with their corresponding frequency response functions. The frequency response function is the Fourier Transform of the strain history divided by the frequency response of the excitation. It is evident from these results that the different excitation methods result in different natural frequencies in the beam being excited. The random shaker excitation appears to result in lower amplitude strain levels overall with more frequency content above 1 KHz. However in both cases the peak strain levels are relatively small; 35 microstrain for the hammer excitation and 10 microstrain for the shaker.

Using these experimental results the operating requirements for the FBG interrogation system were defined as follows in *Table 1*.

Table 1: *Requirements for FBG interrogation system for use with SIDER*

No. of FBGs	Scanning frequency	Dynamic Strain Range	Strain Resolution
Up to 400	5 kHz (to measure frequency content up to 2 kHz)	0–100 microstrain	<1 microstrain

In addition, it was desirable, although not essential that the interrogation system be equipped with an analogue output which would allow the strain history to be directly interfaced to a frequency analyser without any phase lag for the calculation of the frequency response function used in the SIDER analysis.

3 FBG Interrogation

Bragg gratings typically reflect light over a narrow wavelength range and transmit all other wavelengths. They are based on the principle of Bragg reflection, where light propagating through periodically alternating regions of higher and lower refractive index is partially reflected at each refractive index interface. If the round-trip spacing between these regions is an integral number of wavelengths, then each of the partial reflections will add-up in phase and the Bragg condition is satisfied. This results in a narrowband reflection at the phase-matched wavelength. The total reflection under these conditions can approach 100% [2].

The Bragg reflected wavelength λ_B is related to the grating period by

$$\lambda_B = 2n\Lambda$$

where n is the effective refractive index of the fibre and Λ is the period of the grating. Uniform changes in axial strain along the fibre will change the period of the index modulation and result in a shift of the reflected Bragg wavelength which is proportional to the axial strain. Multiple gratings which are designed to reflect at different wavelengths can be spatially distributed along the length of the optical fibre.

The two main approaches for interrogation of FBGs are Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM). The TDM approach involves using a pulsed light source and measuring the response time of the light reflected from the grating to determine its location. All of the gratings in the array tend to be low reflectivity and written at the same wavelength to allow multiple gratings along a single fibre to be interrogated using the same fixed wavelength source. There have been significant improvements in spatial resolution in recent years and there are now commercially available systems which quote a spatial resolution of 1 cm with a strain resolution of ± 1 microstrain (DTS 4300 Luna Innovations). The maximum number of sensors using this type of approach is primarily dependant on the sensitivity of the detection system. This is because the lower the reflectivity of the gratings the more gratings that can be accommodated along the fibre before the source runs out of energy. In the case of the DTS 4300, the maximum number of sensors on a single fibre is specified as 5000. This is significantly more than can be accommodated using a WDM approach, however the resolution and spatial sensitivity comes at a cost and the acquisition times for these types of systems tend to be of the order of one second or longer, making them only suitable for static or slowly changing measurands (such as temperature or shape).

Because FBGs are inherently spectrally encoded, WDM is a more popular approach to FBG interrogation. Most WDM approaches rely on one of two basic configurations: a broadband source with a wavelength scanning detection system or a narrow linewidth scanning laser source with a broadband detector. The latter approach tends to result in a more expensive system as the associated costs with a scanning narrow linewidth source tend to be high, however there is a much higher optical power budget which gives greater capacity for multiplexing and less system noise than with a broadband source.

In addition to the conventional WDM and TDM approaches, it is also worth noting that there are several other FBG systems which rely on alternative demodulation approaches such as optical frequency domain reflectometry and/or intensity based systems which rely on various types of wavelength dependent filtering. Most of these systems are not available commercially or are used primarily as research tools.

There are many commercially available FBG interrogation systems mainly based on WDM most of which have come to market within the past decade. Generally these systems have been designed for distributed strain and temperature sensing applications. There is usually a trade-off with these systems between the interrogation speed and the number of available sensors. A summary of the currently available commercial FBG interrogators and their associated operating specifications are presented in *Table 2*. FBG interrogators employing a TDM approach have not been included in this summary as they are inherently unsuited to dynamic sensing applications such as SIDER. Insensys and Luna Innovations both provide FBG interrogators based on TDM approaches.

4 Assessment of Commercially Available Systems

4.1 Selection of Commercially Available Systems for Review

The commercially available FBG interrogation systems listed in *Table 2* were reviewed with reference to the operating requirements previously stated in *Table 1*. The scanning speed and resolution of the measurement were considered the most important assessment criteria as the multiplexing requirements could be relaxed by sampling the FBG arrays in groups on separate fibres. In addition, in order to facilitate ease of integration with a frequency analyser, the availability of an analogue output and/or external triggering capability was considered as a desirable feature.

Unfortunately the stated performance specifications for each of the systems listed did not provide both the specified scanning frequency and strain sensitivity required to fully characterise the broadband frequency response required for SIDER. Two systems were

Table 2: Commercially available FBG interrogators

Manufacturer	Max Speed(kHz)	No. of sensors	Accuracy (microstrain)	Notes
Micron Optics SM130	2	Up to 500 (125 per ch.)	0.02	
Micron Optics Si925	500	1@500 kHz 4@125 kHz	0.02 (100 microstrain range)	
Micron Optics Si425	250 Hz	Up to 500 (125 per ch.)	0.2	
Smart Fibres (Wx-4)	2.5-20	16 per ch. (4 ch.)	2	Scanning speed is range dependant
FOS&S (Dynosense 300)	3.3	Up to 40 (1 ch.)	5 (*35pm accuracy)	All other products 1Hz scan rate
Optosmart	50	Up to 4	Limited range 1500-3000 microstrain	Gratings at specific wavelengths
IFOS (I*Sense®116000)	5	16 (per module)	±2	
IMON(80D)	2.5	26	6	Spectral separation achieved by high resolution transmission grating
IMON (E)	970 Hz	70	6	(Spectral separation as above)
TFT-FOS (Deminsys)	19.3	8 per channel (4 ch.)	3 (Range (±1000 microstrain)	Uses 850nm source Scanning speed is range dependant
Welltech (FBG210-F10)	10 Hz (2 Hz standard)	64 per ch. (up to 8 ch.)	6	
Welltech (FBG3000)	1	64 per ch. (up to 8 ch.)	±30	
Bayspec-wavecapture™	5	Not specified	20	Volume Phase Grating provide spectral separation
FiberPro IS7000	200 Hz	20 per ch.	<1	Relies on swept fibre laser source
FOS-TA (single sensor)	5	1 per ch. (up to 8 ch.)	±4	Analogue output available
FOS-TA (sensor arrays)	200 Hz	64 per ch. (up to 8 ch.)	±2	
Optilab DFI	3.7	25 per ch. (up to 4 ch.)	4	
FiberSensing FS5500/FS5600	10	4 per ch. (up to 4 ch.)	0.02 (±8.3 microstrain repeatability)	Gratings must be written to specific wavelengths
FiberSensing FS5100/FS5200	100 Hz (1 Hz standard)	20 per ch. (up to 4 ch.)	~2	

selected which had operating specifications which came close to fulfilling the two main section criteria of speed and sensitivity. These will be referred to as System A and System C, a third system which was available in the laboratory (System B) was also selected for comparison.

Each system was assessed under the following five criteria: Distributive Capacity (number of sensors), strain range, strain resolution, frequency range and interfacing capability (analogue output).

4.2 Comparison Results

4.2.1 Comparison Summary

Table 3 compares the three commercial interrogation systems tested in this study.

Table 3: *Comparison of reviewed interrogation systems*

Property	System A	System B	System C
Channels	4	4	4
FBGs/Ch. (Max)	16	128	80
Simultaneous interrogation	Yes [see note 1]	Yes [see note 1]	Yes [see note 1]
Scan freq.	2.5 kHz (up to 20 kHz with reduced λ range)	250 Hz	1/2 kHz [see note 2]
Wavelength range	40 nm (1528-1568)	50 nm (1520-1570)	80 nm (1510-1590)
Data output interfaces	Ethernet (UDP-IP) only [see note 3]	Ethernet (UDP-IP) [see notes 3,4]	Ethernet (UDP-IP) only[see note 3]
External triggering	Software only (customised)	N/A [see note 4]	Hardware [see note 5]
Recorded data format	Tab delimited text (timestamp & wavelengths)	Tab delimited text [see note 4]	Tab delimited text (timestamp, sensor count & wavelengths)
Typical noise level (p-p)	10-50 microstrain	<10 microstrain [see note 4]	4-8 microstrain

1. Small time delay between individual FBG sensors relative to laser scan rate.
2. Maximum available is 2 kHz, unit tested was 1 kHz.
3. Interfaces with custom LabVIEW software.
4. Detailed testing not performed as the scanning frequency was much too low for SIDER requirements.

5. Provides synchronous capture with other proprietary units, or external trigger (up to 1ms deviation) for other devices.

4.2.2 Number of Sensors

For System A, the maximum number of sensors that can be interrogated at any one time is 64. However, when higher scanning frequencies are used, this number is reduced (approximately half the number of sensors for a doubling of the frequency). In order to meet the requirements for SIDER either multiple units or a switching device to interrogate the sensors in groups would be required. System C allows for simultaneous interrogation of up to 320 sensors. This comes far closer to the stated requirements. System B can incorporate 512 sensors across 4 channels which would meet the requirements without the need for sampling in groups.

4.2.3 Scanning Frequency

System C has a maximum scanning speed of 2 kHz which is only sufficient to characterise frequency content of up to 800 Hz rather than the required 2 kHz. System A did have the required scanning speed (user selectable up to 20 kHz); however this higher scan rate comes at the cost of strain resolution. As mentioned earlier, the higher sample rate also limits the number of sensors that can be interrogated. The scanning speed of System B is 250 Hz which limits its useful range to measurement of frequencies below 100 Hz. This is well-below the requirements for SIDER and so further assessment of this system was not conducted.

4.2.4 Strain Range

All of the units tested had no issues measuring strains with a magnitude of 100 microstrain and over. For the low end of the scale, the range was limited by the resolution.

4.2.5 Strain Resolution

As mentioned earlier, the higher scan rate offered by System A comes at the cost of strain resolution. The demodulation system required the spectral profile of the grating to have a reasonably large full-width-half-maximum (FWHM) and at a 5 kHz scanning speed only 6-8 points were used in the peak detection algorithm. The strain resolution of this system was heavily dependant on the location of these points within the FBG reflection spectrum and ranged between 10 and 40 microstrain. Also, while strain resolutions of approximately 10 microstrain could be obtained without too much difficulty on individual gratings, when interrogating arrays it was extremely difficult to get a consistent resolution across all of the gratings.

For System C, when scanning at full speed (without averaging), the maximum strain resolution which could be reliably achieved was 5-10 microstrain. System C also yielded fairly consistent resolutions between gratings in an array. This was a marked improvement over System A, but it still did not meet the requirements. While averaging could improve the results this would reduce the effective sampling speed of the system which was already too low.

4.2.6 Analogue Outputs and Triggering

None of the interrogators investigated had an analogue output capability and all relied on on-board digital signal processing and external data transfer via Ethernet connection. Also, the literature review revealed that there appeared to be no commercially available systems with the required scanning range and sensitivity which also had an analogue output.

External triggering was also fairly limited in the devices tested. System A initially had no external triggering capability. It was possible to implement a mechanism for external triggering via software on the host PC. However, due to the nature of the communications protocol between the device and the PC, there was no way to reliably synchronise the data capture with the trigger source.

System C had hardware triggering inputs and outputs, however these are not synchronised to the internal laser scan and as a result there can be a latency of up to a millisecond between triggering and data capture.

4.3 Conclusion

The results of this investigation into available COTS FBG interrogation systems indicated that there was no system available that would satisfy all requirements. The System A interrogator met the frequency requirements; however strain sensitivity levels were far from adequate. System C had far better sensitivity, yet still not sufficient for the requirements of SIDER; it also does not have the desired frequency response. In addition, neither device was capable of providing an analogue output, or a phase-accurate external trigger. As a result of these findings, an alternative method of FBG interrogation was investigated, and is covered in the next section.

5 Intensity Based Interrogation

5.1 Basic Principle

Intensity based interrogation involves tuning a laser source with a narrow line-width to a wavelength corresponding to the midpoint of the leading or trailing slope of the FBG. When a strain is applied to the grating the spectrum will shift, causing the transmittance at the tuned wavelength to increase or decrease (see *Figure 3*). This can be quantified by measuring the amount of transmitted or reflected light with a photodiode. For small strains, where the wavelength shift is less than half the width of the slope, the relationship between the applied strain and the light intensity measured by the detector is approximately linear.

The fundamental design of the grating interrogation system has been previously described in the literature for the detection of Lamb waves[3]. A schematic diagram is shown in *Figure 2*.

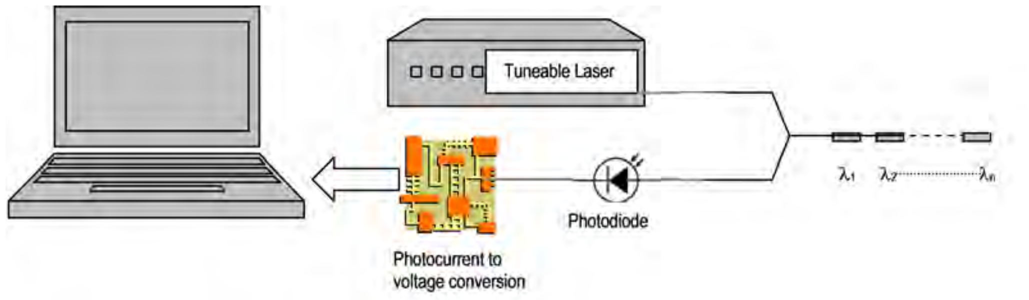


Figure 2: *Schematic diagram of intensity based FBG interrogation system*

Since the laser is static, rather than sweeping as with the WDM interrogation systems, the frequency response can be very high and is limited only by the response characteristics of the strain transfer to the fibre, the photodetector and the sampling instrument. The magnitude of strain that can be measured is limited by the shape of the FBG spectrum. This is because the wavelength shift induced by an applied strain must not be larger than half the width of the rising or trailing edge of the grating spectrum.

The intensity based system yields both excellent frequency response and strain sensitivity when compared to wavelength-based demodulation approaches. It also provides a direct analogue output from the photodiode which avoids phase-lag issues introduced by the digital processing performed by most commercial interrogation systems.

5.2 System Limitations

Although this system provides the sensitivity and frequency response that were lacking in the WDM systems, it comes at a cost. Given that there is only one laser source and one photodiode, only a single grating can be interrogated at a time. Therefore in this form, if multiple sensors are to be interrogated, human interaction is required to locate and tune to the desired wavelengths for each grating, and to connect each array in turn. During preliminary testing this proved to be a very inefficient process, and significantly increased the time required to interrogate a series of FBG arrays. In order to make interrogation of multiple gratings practical, this human interaction must be minimised as much as possible. To this end, the system has been modified to include automated wavelength scanning and a fibre switching capability.

5.3 Modified Design

In the original system the operator must first connect the output (normally connected to the photodiode) to the internal light meter in the tuneable laser, then perform a wavelength scan across the array. Following the completion of the scan, they must identify and record

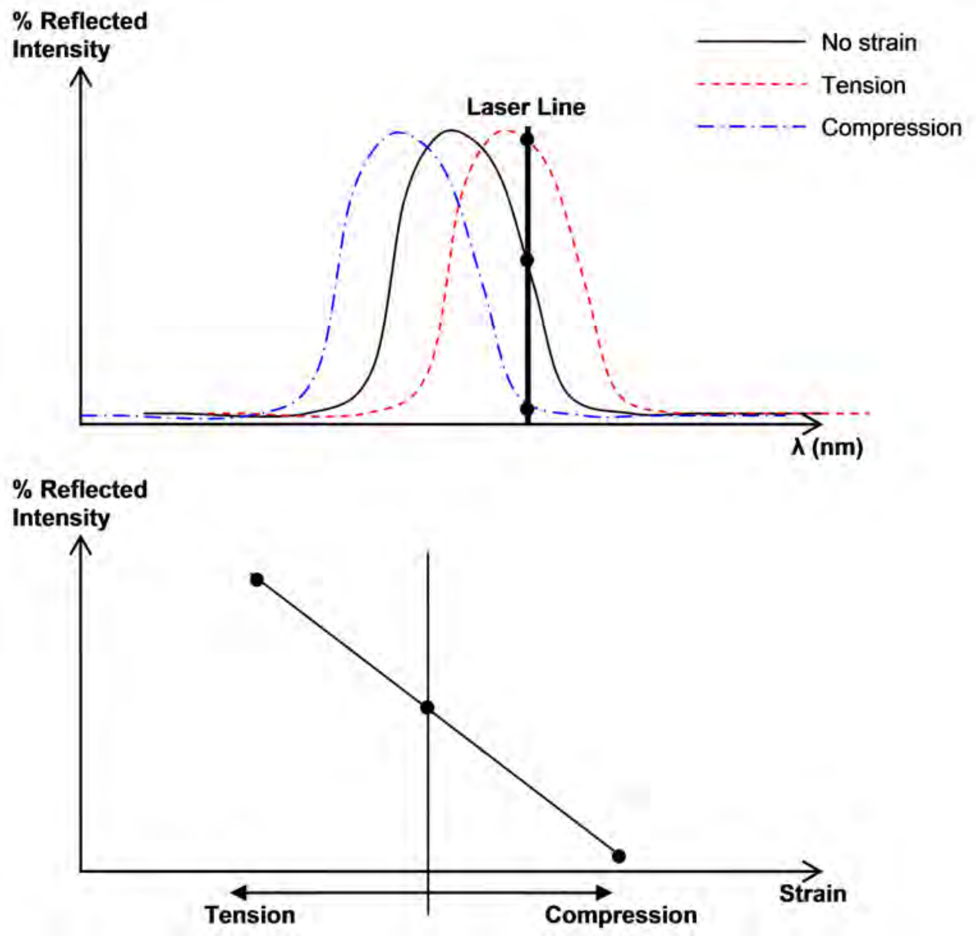


Figure 3: *Principle of operation of intensity based FBG interrogation system*

the wavelengths of the desired tuning points. Finally, they need to manually enter each wavelength into the system before interrogating the corresponding FBG. This process is very involved and time consuming, making the system impractical for the interrogation of large scale sensor networks.

5.3.1 Key Improvements

The improved system seeks to address these issues by:

- Automating the process of scanning an array and locating the desired tuning point for each FBG.
- Automatically switching between the internal light meter in the tuneable laser and the external photodiode.
- Providing a mechanism for the operator to quickly tune to each FBG, and additionally to switch between multiple connected arrays.

- Providing an external trigger to inform the data acquisition device when the system is ready.
- Offering a fully automated mode which advances through all the steps required to interrogate a series of connected FBG arrays.

In the improved interrogation system, the number of gratings per fibre is limited only by the bandwidth of the swept laser source and the number of optical fibres is determined by the number of switches on the module[1].

5.3.2 Operation of Modified System

The automated system makes use of a GPIB[2] interface to control the tuneable laser source in addition to one or more optical fibre (OF) switching modules. A laptop running custom-developed LabVIEW software acts as the controller for the system, offering both partial and full automation of the interrogation process. The tuneable laser provides both the laser source and an in-built detector to characterise the gratings. An OF switching module allows the system to switch between the internal detector in the tuneable laser source module and the external photodiode. A second OF switching module is used to select between multiple FBG arrays. It should be noted that the system could be modified with minimal effort to use a single switching module with MIMO (multiple inputs, multiple outputs) capability. A schematic diagram of the improved system is shown in *Figure 4*.

In the automated mode, the laser scans across the FBG array within a given fibre and all the FBG peaks within the array are identified. The wavelength corresponding to the midpoint[3] of the linear region of the leading or trailing edge is also noted for each grating. The laser then tunes to the first of these points, switches from the internal light meter in the tuneable laser to the external photodiode and sends an external trigger to the frequency analyser. This notifies the frequency analyser that the system is ready for interrogation. The analogue signal from the photodiode can then be measured by the frequency analyser while the system waits for a user-defined time interval[4]. Then the system switches back to the internal power meter and tunes the laser to the next FBG. The process of tuning, switching the output to the photodiode, triggering and waiting repeats for each grating on the array. When the last grating in the array is reached, the second OF switch module switches to the next fibre and the whole process repeats. The system can be configured to scan individual arrays immediately before they are interrogated or pre-scan all connected arrays before the interrogation run starts.

In manual mode, the system operator is responsible for configuring the wavelength range of each scan, initiating the scan and selecting which array or grating to tune to. Switching between the photodiode and the internal light meter, and identification of tuning points[5] remains automated. This mode is also used to aid in preparing the array config-

[1] Presently the array switching capacity is 7

[2] General Purpose Interface Bus

[3] This is usually identified as the point where reflected power is 50% of that at the peak

[4] The system can also run in a semi-automated mode where the action of progressing to the next sensor is initiated by the operator, rather than after a pre-set time period

[5] The operator can adjust the parameters used for tuning point selection

uration files for use with the fully automatic mode. More details of the system operation are provided in *Appendices A–C*.

The gradient of the reflection spectrum at each tuning point used is also recorded for the purpose of calibrating the data for the frequency analyser. This is done to ensure that arrays of differing shapes and a mixture of leading and trailing edges can be used for the same data set (see *Section 6.2.3*).

5.4 Unresolved Limitations

Some limitations associated with this system remain unresolved due to the nature of this type of interrogation. The system can only interrogate on a grating-by-grating basis and although good strain sensitivity (<1 microstrain) has been achieved, the strain range is limited by the size and shape of the grating's reflection spectrum (typically of the order of 80-100 microstrain).

5.5 Overview of Improved System

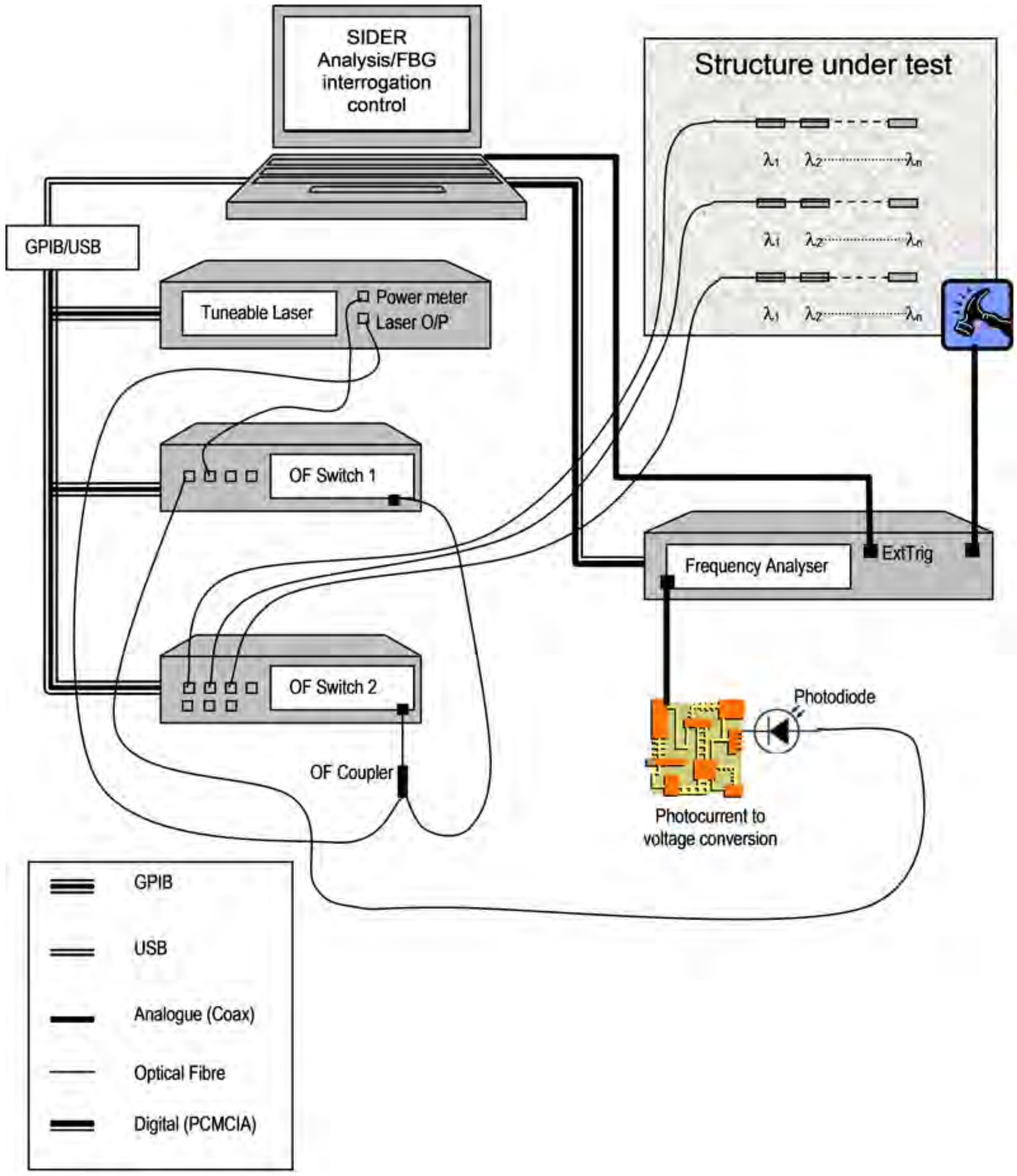


Figure 4: Schematic of the automated intensity based distributed interrogation system with analogue output for incorporation into frequency analyser and SIDER

6 Optimisation of Fibre Bragg Grating Sensors for Response Measurement

The response characteristics of FBG sensors can be changed by modifying the profile of the grating reflection spectrum. Presumably, when using intensity interrogation, the ideal shape of a grating will depend on the magnitude of the response being measured. The maximum peak-to-peak strain amplitude of the response is the prime concern here, as when using intensity based interrogation the total range is fairly small. The method of structural excitation used has the largest influence on strain amplitude of the induced vibrations.

6.1 Excitation

Impact excitation (with an instrumented hammer) and shaker excitation (with a random input) have both been tested with the intensity interrogation method.

6.1.1 Impact Excitation

Impact excitation typically results in a high amplitude response concentrated in the lower frequencies. Testing has showed that the chance of saturating a sensor with this excitation type is very high unless minimal force is used. This type of excitation requires that the grating profile be optimised for maximum range.

6.1.2 Random Shaker Excitation

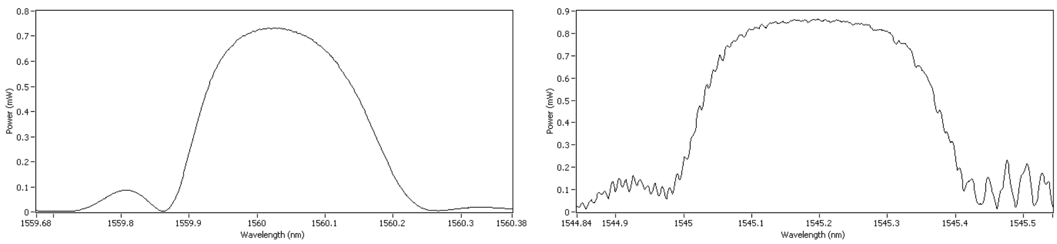
Excitation with a random input signal from an electrodynamic shaker with a force capacity of 1 lb results in a relatively low amplitude response and a fairly even distribution of power versus frequency in the 0-2 kHz range. The induced strains from this method of excitation are low and so saturation is usually not an issue except when using gratings with a very limited range.

6.2 Grating Design

The shape of the grating profile can be controlled by a combination of factors. The underlying grating profile shape is determined by the apodization profile applied to the index contrast. In addition the steepness of the rising and trailing edges for any given profile is dependent on the reflectivity or strength of the grating, with stronger gratings tending to have steeper gradients. The grating strength is in turn determined by the physical length of the grating and by the degree of refractive index contrast within the grating.

6.2.1 The Importance of Linear Reflection Profiles

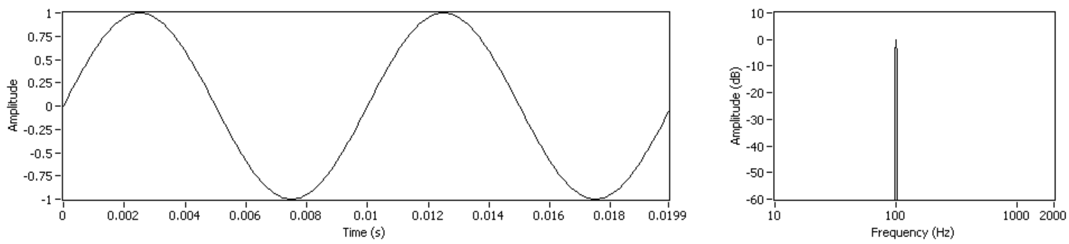
A monotonic reflection profile with linear edges is critical to ensure that the measurements from the sensor accurately reflect the physical strains. An example of this type of profile is shown in *Figure 5(a)*.



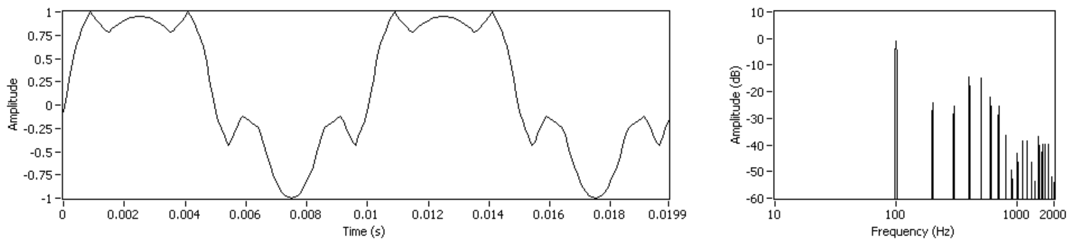
(a) Good (b) Bad

Figure 5: *Comparison of FBG reflection profiles*

Non-linearities and oscillations in the reflection profile (*Fig.5(b)*) can be caused by faults in the writing process or physical anomalies (such as cracks) in the fibre. Anomalies that are not located in a part of the fibre experiencing strain variations may not affect the performance of the sensors. However, if the non-linearities were formed in the writing process or by physical anomalies in a section of fibre undergoing strain variations, potentially severe distortions of the FBG sensor output will result. *Figure 6* illustrates the effect a non-linear edge can have on measurements made with intensity interrogation.



(a) Time History (Input) (b) Spectrum (Input)



(c) Time History (Output) (d) Spectrum (Output)

Figure 6: *Simulation of measured output for non-linear grating profile (c-d) for a given input (a-b)*

Clearly the original sine-wave has been severely distorted and the oscillations in the

FBG profile have introduced significant noise in the higher frequencies. While the original signal is still resolved in the spectrum, if the original signal contained higher frequency components, these would be indistinguishable from the noise.

6.2.2 Grating Shape vs. Sensitivity

The gradient of the leading or trailing edge of a grating defines the sensitivity and strain range of the sensor. A grating with a steep edge gradient will have a small range and high sensitivity to wavelength shifts. Conversely a shallow edge gradient will result in a broader range and lower sensitivity.

6.2.3 Leading vs. Trailing Edge

The primary change that will arise from interrogating at the rising edge as opposed to the trailing edge (or vice-versa) is a positive-negative flip of the recorded strain values. There will also typically be a difference in the gradient, however this is less relevant as there is usually a variance in edge gradient between different gratings on the same array regardless.

Both of these issues can be overcome by measuring the gradient of the edge under interrogation and using the resulting factor to calibrate the measurements. This has been built into the software developed to control the interrogation system as detailed in *Appendix D*.

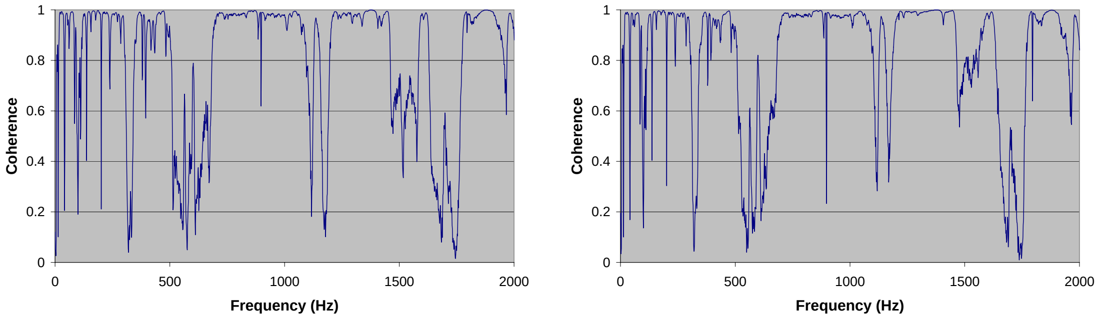
6.3 Coherence

The coherence function gives a measure of the correlation between the input and output of a linear system with respect to frequency. Values of coherence fall in the range of 0–1, where a 1 indicates a perfect correlation between input and output data and 0 indicates no correlation. Low coherence typically indicates that either the system is non-linear or noise is entering the measurements.

6.3.1 Effect of Sensitivity on Coherence

It is logical to assume that interrogating an edge with a steeper gradient (more sensitive) will produce a result with better coherence than an edge with lower sensitivity. The reasoning is that a steeper gradient will give a larger measured output signal for the same wavelength shift — hence a better SNR[6] and coherence should be achieved. However, experimental results have shown otherwise as illustrated by *Figure 7*.

[6] Signal-to-Noise Ratio



(a) Leading edge (steeper gradient)   (b) Trailing edge (shallower gradient)

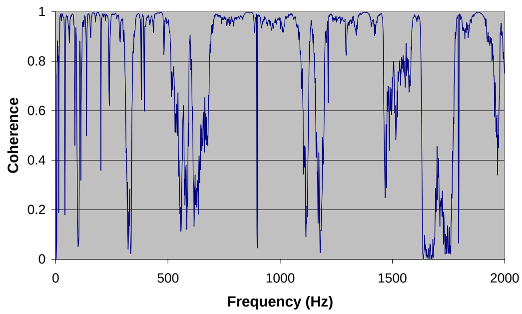
Figure 7: *Coherence (averaged from 3 tests) comparing the effect of edge gradient*

For the test result in *Figure 7* a single grating was used to measure strain in a composite beam under shaker excitation. The leading edge of the grating spectrum had a steeper gradient than the trailing edge — thus by interrogating each edge in turn a comparison between different edge gradients could be made.

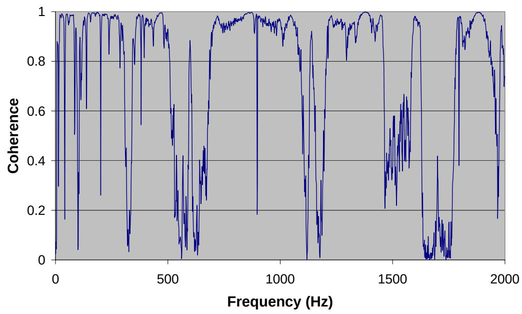
The difference between the results from each edge appears to be minor. If anything, the coherence for the shallower gradient is slightly higher overall. One potential explanation for this could be that wavelength instability in the tuneable laser is a primary source of noise. As the increased gradient only serves to increase the magnitude of the measured change in power relative to wavelength shift, this type of noise would be amplified along with the signal. Another possibility is that the shorter range associated with the higher gradient is causing the wavelength to shift beyond the linear region of the edge. This non-linearity in the system would cause coherence to decrease.

6.3.2 Effect of Excitation Energy on Coherence

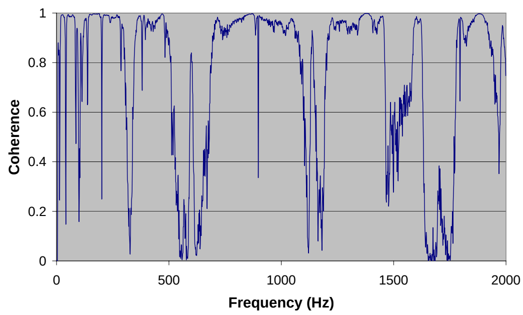
If low coherence between the measured input and output signals is the result of noise or inadequate resolution, it stands to reason that increasing the input signal strength will lead to an improvement. To test this, a single FBG was bonded to a glass-composite beam which was subjected to shaker excitation with a random input signal. The gain level for the shaker was set to three different points and the FBG was interrogated for each level. The coherence for the FBG at each level of excitation was calculated and the results can be seen in *Figure 8*.



(a) Base level



(b) Twice the force



(c) Three times the force

Figure 8: *Coherence comparing the effect of excitation energy*

The results show no significant difference in the coherence between the different levels of excitation. This indicates that inadequate resolution is not an issue and that the cause of low coherence (noise or non-linearity in the system) increases in conjunction with the signal.

6.4 Conclusion

The ideal grating profile should theoretically be based on the type of excitation being used in the system under measurement. For impact excitation this means a large range is critical and for shaker excitation high sensitivity would be more desirable. However testing has shown that an increase in sensitivity did little to improve the quality of measurements. Therefore, use of gratings optimised for range can be recommended for both excitation types — this has an added benefit that either method of excitation can be used without requiring the use of a different set of sensors. Regardless of the method of excitation, the most important aspect of the grating shape is the linear response to wavelength on the leading or trailing edge.

The results suggest that at frequencies which are off-resonance, there is no significant strain present and the fundamental noise level for the system is dominant which obviously produces very poor correlation with the input signal. At resonance the strains generated are well-above the noise threshold and increasing the excitation energy appears to have no effect on the coherence.

7 Conclusions

Preliminary measurements of the in-plane strain levels induced by structural vibrations in a test composite beam have been shown to be small with some frequency components being at the sub-microstrain level particularly in the 1–2 kHz frequency range. The requirements for an FBG interrogation system to be able to perform these measurements are therefore quite demanding in terms of sensitivity, speed, range and distributive capacity. A literature review was carried out investigating all the COTS dynamic FBG interrogation systems and their stated specifications with these requirements in mind.

Unfortunately none of the currently-available COTS systems investigated provided both the specified scanning frequency and strain sensitivity required to fully characterise the broadband frequency response required for SIDER. However, it should be noted that there has been a lot of activity in the transition to market of FBG interrogation systems over the past decade and the performance specifications of these systems are continually improving to meet market requirements.

Two COTS systems were assessed which had operating specifications which came closest to fulfilling the two main selection criteria of speed and sensitivity. A third (COTS) system which was also available in the laboratory was included for comparison. The conclusions from these experimental evaluations were that none of the systems had the capability to provide the measurements required for SIDER.

On the basis of these findings an FBG interrogation system which had been previously developed for the detection of Lamb waves was modified to allow for both triggered single impact and continuous time-windowed excitation. The system was automated to allow for scanning of FBG arrays across several fibres using a fibre optic switch and an analogue output was provided for interfacing to the OROS frequency analyser.

The new system exhibited good strain sensitivity (<1 microstrain) and an excellent frequency response. However it has a fairly limited strain range which is dependent on the size and shape of the grating's reflection spectrum but is of the order of about 100 microstrain. This range is obviously not sufficient to contend with the larger strains which a structure may experience due to manoeuvre loading however as these strains are pseudo-static, the system should be able to correct for these underlying strain levels as long as they do not change substantially during the course of the dynamic response measurement.

The coherence levels for the FBGs at off-resonant frequencies are still substantially less than those provided by the accelerometer measurements and it remains to be seen whether they will be sufficiently high to provide a signal of suitable quality for SIDER. It may be necessary to limit the analysis to frequency ranges which exhibit resonance.

The next stage of the program will be to use this interrogation system with a series of FBG arrays on a damaged test specimen. The specimen will be excited and the response from each FBG measured to provide a spatially distributed dynamic strain profile across the specimen. These inputs will be used by SIDER to provide a contour map of any structural stiffness variations caused by the damage.

8 Acknowledgements

The authors gratefully acknowledge the contributions of Mr Chris Rider from DSTO for assisting with the vibrational analysis experimental work and Mr Travis Nuyens (an industry based learning student from Swinburne University) for fabricating the FBG sensors used in this report.

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Appendix A Program Operation Modes

Description of the modes of operation of the Tuneable Laser Control software.

A.1 Manual Operation

In manual operation mode the operator is responsible for

- Setting scan parameters
- Controlling array selection
- Executing array scans

Switching the output between the photodiode and the internal power meter on the laser is fully automated. Peak detection and tuning point selection is partially automated — the operator is required to supply the detection parameters and the desired tuning edge.

All configuration data can be saved for later use — this is actually necessary to enable the automatic operation.

A.2 Semi-Automatic Operation

In this mode all setup parameters are loaded from pre-saved data. Switchbox operation and array scan execution is fully automated so the operator only controls when to switch to the next sensor. This mode is recommended when interrogating a series of sensors/arrays with manual excitation (i.e. human operated hammer excitation) where the time to interrogate each sensor is variable/unknown.

A.3 Full-Automatic Operation

Full-Automatic operation is much the same as semi-automatic operation. The key difference is that the operator does not directly control the selection of sensors, rather the system automatically selects the next sensor after a pre-defined time period has elapsed. This mode is recommended when automatic or continuous excitation methods (i.e. shaker) are used.

A.3.1 Pre-scanning

When using full-automatic mode the operator must choose between scanning each array immediately before it is to be interrogated or pre-scanning all the arrays before the interrogation run begins. Pre-scanning may be beneficial if the excitation method is continuous (i.e. shaker excitation) as the quality of array scans will be negatively affected if run whilst the FBG wavelengths are shifting. However pre-scanning could be undesirable if the duration of the interrogation run is very long as natural temperature variations can cause FBG wavelengths to shift away from the optimal interrogation point between when the array is scanned and the sensor is interrogated.

Appendix B Program Operational Details

B.1 Full-Automatic Mode

Full-Automatic mode requires that each connected array has already been scanned with the desired setup parameters and the configurations saved. A list of the saved configurations for each array and the number of gratings on each array must also be created. This can all be done from within the software.

1. Switch to first array
2. Load previously created configuration for array
3. Switch to laser power meter
4. Scan Array
5. Locate peaks and tuning points
6. Tune to first FBG
7. Interrogate FBG:
   (a) Update controller screen readings
   (b) Switch to photodiode
   (c) Send external trigger (parallel port)
   (d) Wait (user-defined period)
8. Switch to laser power meter
9. If not last FBG:
   (a) Switch to next FBG
   (b) Return to step 7

   If last FBG, not last array:
   (a) Switch to next array
   (b) Return to step 2

   Otherwise:
   (a) Stop

B.2 Full-Automatic Mode (with pre-scan)

Requirements for this mode are the same as for full-automatic mode without pre-scanning. The only significant difference in this mode is that all arrays are scanned before interrogation begins rather than scanning each array immediately before it is to be interrogated.

B.2.1 Pre-scan

1. Switch to first array
2. Load previously created configuration for array
3. Switch to laser power meter
4. Scan Array
5. Locate peaks and tuning points
6. Save spectrum and location of peaks/tuning points
7. If not last array:
   (a) Switch to next array
   (b) Return to step 2

   Otherwise:

   (a) Wait for interrogation to start (see below)

B.2.2 Interrogation

1. Switch to first array
2. Load saved config, spectrum, and peaks/tuning points for array
3. Tune to first FBG
4. Interrogate FBG:
   (a) Update controller screen readings
   (b) Switch to photodiode
   (c) Send external trigger (parallel port)
   (d) Wait (user-defined period)
5. Switch to laser power meter
6. If not last FBG:
   (a) Switch to next FBG
   (b) Return to step 4

   If last FBG, not last array:

   (a) Switch to next array
   (b) Return to step 2

   Otherwise:

   (a) Stop

B.3 Semi-Automatic Mode

Semi-Automatic mode operates in almost exactly the same manner as full-automatic mode (without pre-scan). The only difference is that the program waits for the operator to press a button before continuing to the next sensor rather than waiting for a pre-set period.

B.4 Manual Operation

Under manual operation the parameters for the scanning and peak detection are configured by the operator. Some parts of the program remain automated and are described below.

B.4.1 Perform Scan

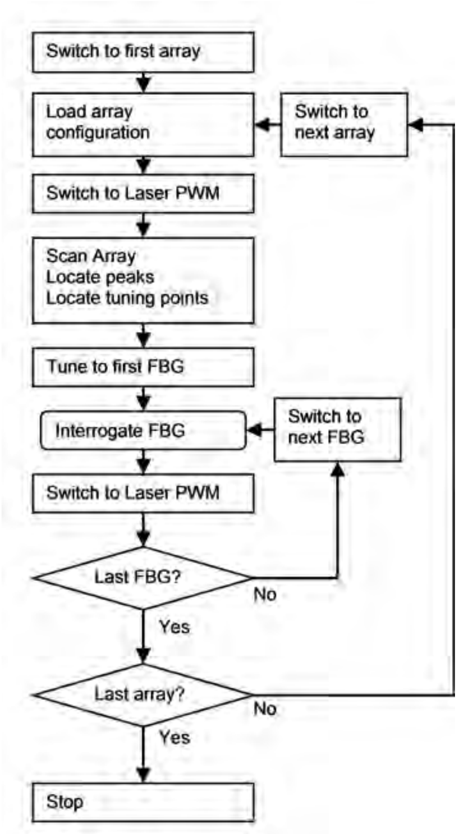
1. Switch to laser power meter
2. Scan Array (scan range/resolution/power/peak detection parameters configured or loaded from file by operator)
3. Locate peaks and tuning points
4. Tune to first FBG
5. Interrogate FBG:
   (a) Update controller screen readings
   (b) Switch to photodiode
   (c) Send external trigger (parallel port)

B.4.2 Tune to FBG

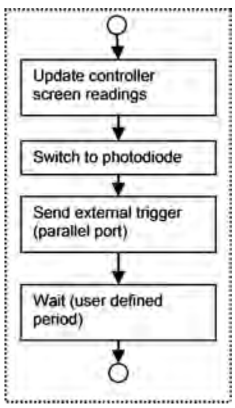
1. Switch to laser power meter
2. Tune to next/previous FBG
3. Interrogate FBG:
   (a) Update controller screen readings
   (b) Switch to photodiode
   (c) Send external trigger (parallel port)

Appendix C Program Flowcharts

C.1 Flowchart for Full-Automatic Mode

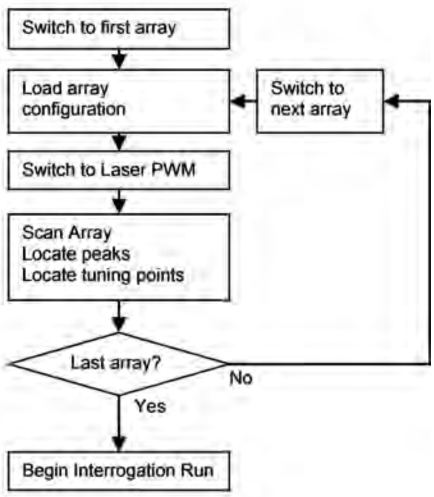


C.1.1 Interrogate FBG (details)

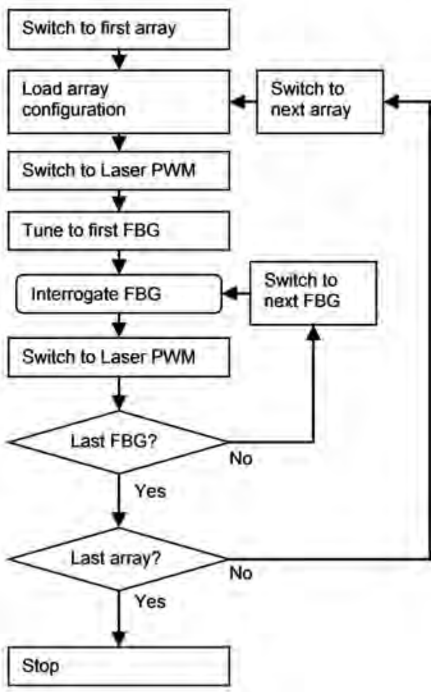


C.2 Flowchart for Full-Automatic Mode (with pre-scan)

C.2.1 Pre-scan



C.2.2 Interrogation Run



Appendix D Sensor Calibration

Calibration enables the use of gratings of different spectral shapes and a mix of leading and trailing edges.[7]

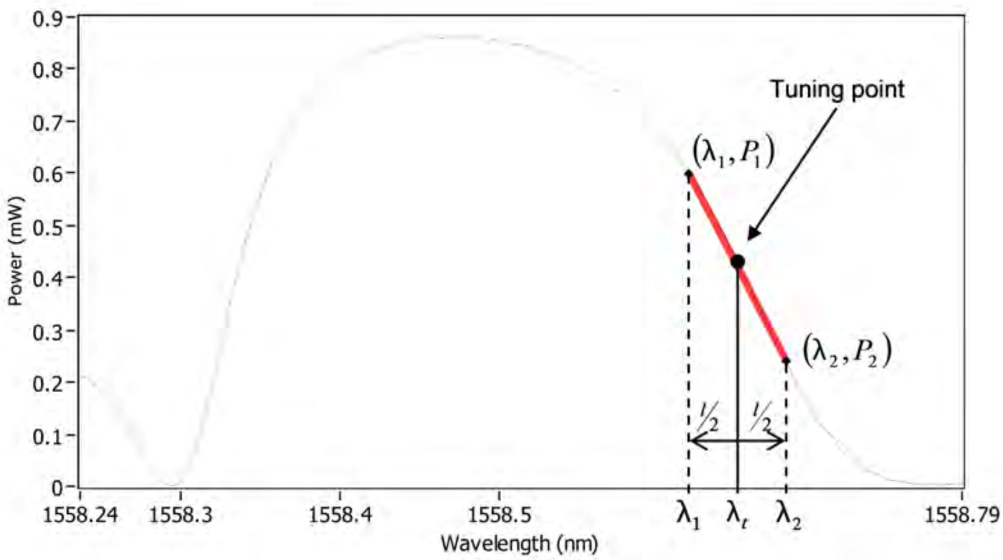


Figure D1: *FBG sensor calibration for intensity interrogation*

l = Calibration length (approx. width of linear range)

λ_t = Tuning wavelength

$$\therefore \lambda_1 = \lambda_t - \frac{l}{2}$$
$$\lambda_2 = \lambda_t + \frac{l}{2}$$

Gradient can therefore be calculated from[8]

$$\frac{P_2 - P_1}{\lambda_2 - \lambda_1} = \text{ edge gradient (mW/nm)}$$

A FBG sensor with steeper edges will produce a larger output signal and will also have a larger gradient. Therefore the recorded data can be calibrated by dividing it by the gradient. This also compensates for the use of both leading and trailing edges as the calibration gradient will be positive or negative depending on the edge used.

[7]This allows the cleanest/most suitable edge from each grating to be chosen

[8]Calibration can alternatively be generated by fitting a line of best fit to the points between λ_1 and λ_2

Appendix E System Operation Documentation

E.1 Configuration Screen

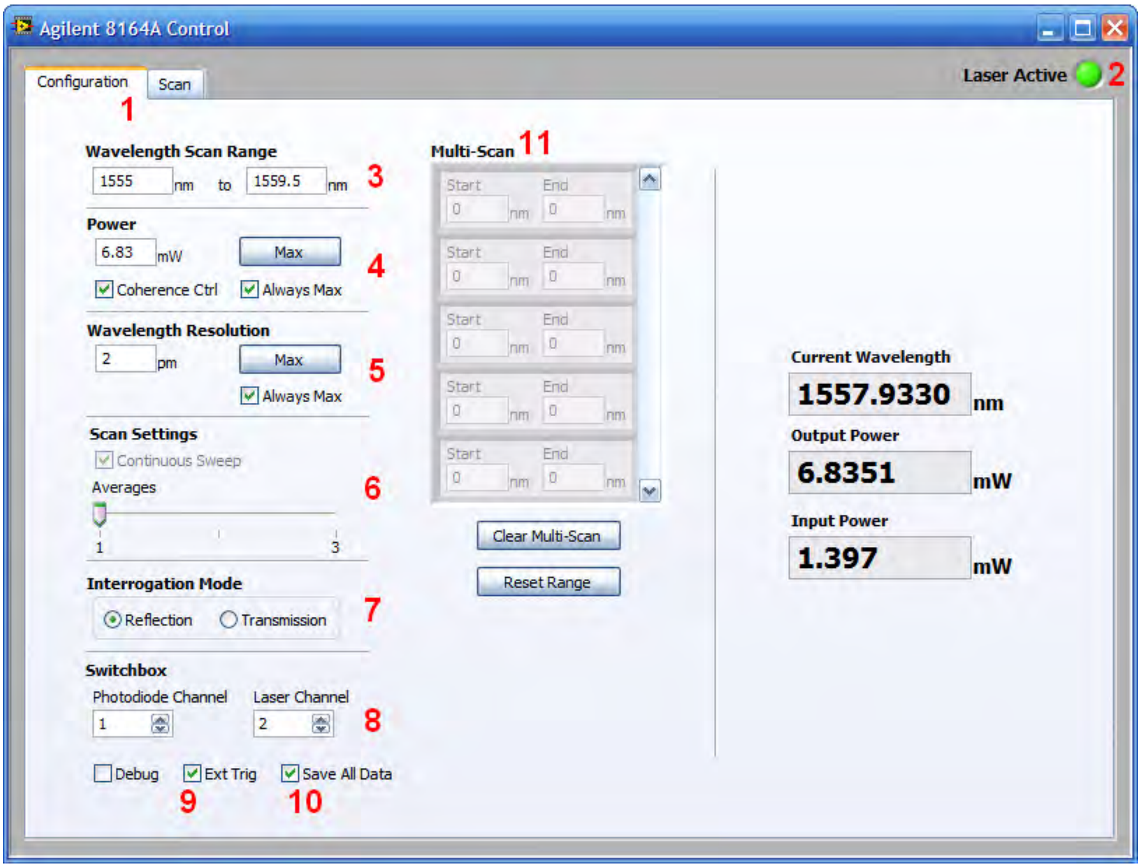


Figure E1: *Configuration Tab*

1. Switch between configuration and scan modes.
2. Click to activate/deactivate laser output.
3. Wavelength range over which to perform scan.
4. Laser power settings: set the power output level of the laser and enable/disable coherence control. To set power to maximum allowed for selected scan range select 'Max' or 'Always Max'.
5. Set the resolution to use when scanning. To use highest resolution allowed for selected scan range select 'Max' or 'Always Max'.
6. Set the number of averages to use when scanning (usually unnecessary).
7. Set whether to scan in reflection or transmission *(note: transmission mode will not work with multiple connected arrays)*.
8. Set the switch-box channels for the photodiode and laser power meter.
9. Send external trigger (via parallel port) whenever selecting a new FBG sensor.
10. When in automatic mode, save all data collected. When in manual mode, save all data (not just plot image) when saving a scan.
11. Configure multiple scan ranges.

E.2 Scan Screen

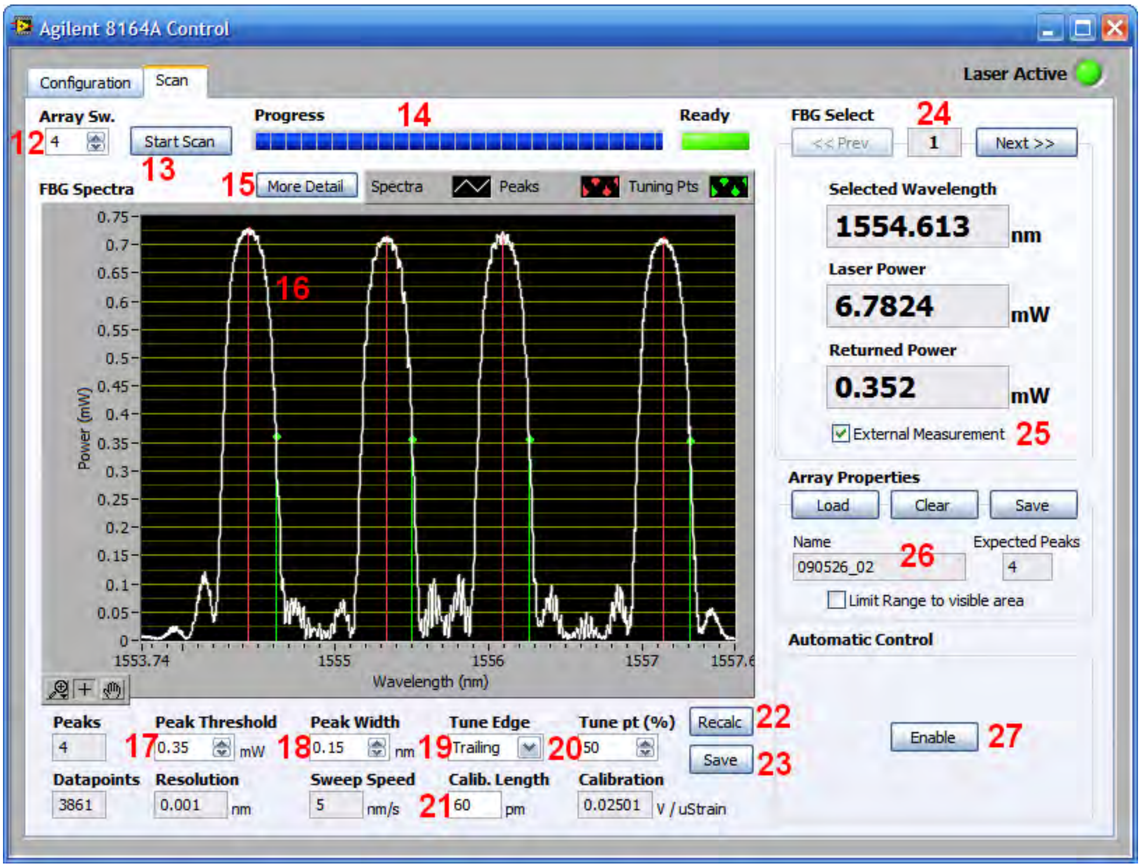


***Figure E2:** Scan Tab*

12. Array selector switch control — use this to select the desired FBG array with the second switch-box.
13. Begin a scan across the preset wavelength range.
14. Indicates progress of the wavelength scan — 'Ready' is green when scan is complete and peak detection/FWHM analysis has completed successfully.
15. Rescan gratings with best resolution by scanning array in sections.
16. Double-click on red peak lines to configure which edge and how far up the edge to tune to for individual gratings.
17. Peak threshold — set to ignore peaks below this level.
18. Set to approx half (or a bit under) the FWHM of the FBGs being interrogated.
19. Set all gratings to tune to leading or trailing edge.
20. Percentage of peak power to use when selecting tuning point.
21. Set width in nm to use for calibration gradient.
22. Perform peak detection/FWHM analysis again on existing data (use if modifying parameters 15-19 to skip re-scanning).
23. Save the current FBG spectra plot in bitmap and text (tab-delimit) format.
24. Select next/previous FBG in array / indicates currently selected FBG.
25. If unchecked, will never switch to photodiode (testing purposes only).

26. Save/Load array configuration — this stores wavelength range, power, resolution, peak detection parameters (more detail in *Figure E3*).
27. Enable automatic control mode — when clicked will open config dialog (*Figure E4*).

E.2.1 Array Properties

Figure E3: *Save/Load array config*

1. Load a previously saved array configuration – this will fill in parameters to be used on next scan.
2. Clear the currently loaded array config – this will stop verification of the number of peaks found against the number in the loaded config.
3. Save the current scan and peak detection parameters and the number of peaks found to a file for later use.
4. Name of the currently loaded configuration.
5. When performing a scan, the number of peaks found will be checked against this number, if there is a mismatch the scan will fail.
6. If checked, when saving a config, the saved wavelength scan range will be confined to the area currently displayed in the spectrum plot.

E.3 Automatic Control

When using automatic control mode, the program must be provided with:

- a list of names and sizes (sensors per array) of pre-saved configurations for each array
  - must be ordered in the same manner as the connections to the switch-box
  - configuration must be saved to same location as list
- the time to wait on each FBG before moving to the next sensor

E.3.1 Configuration

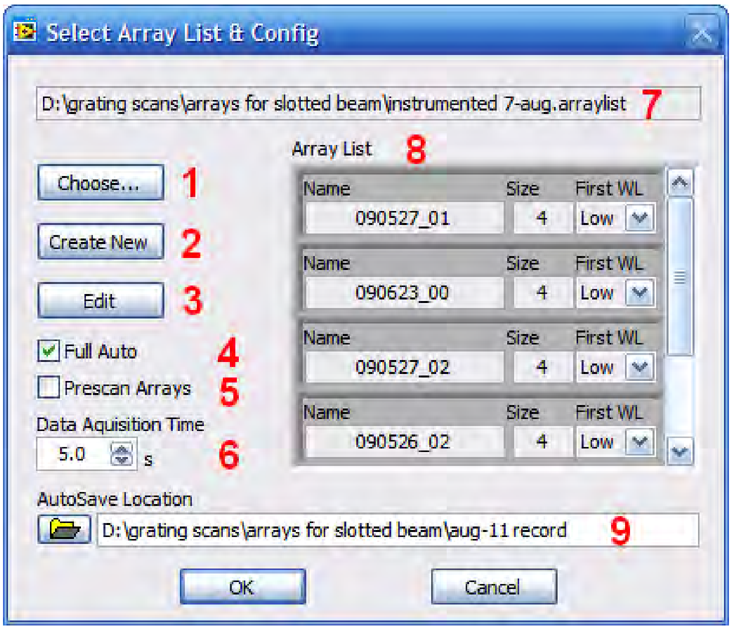


Figure E4: *Array list selector/Auto mode config*

1. Choose a saved array list file to load.
2. Create a new array list file.
3. Edit the currently loaded array list file.
4. Choose between semi-auto and full-auto operation modes
5. Pre-scan all arrays in list before interrogation begins rather than when switching between arrays.
6. Set the time to wait on each FBG before moving to the next sensor.
7. Indicates the location of the currently loaded list.
8. Preview of the currently loaded list.
9. Choose the location to save scan, setup and calibration data.

E.3.2 Array List Editor

Array lists can be created or edited using the editor in *Figure E5*. The editor is accessed by selecting 'Create New' or 'Edit' in the array list selector (*Figure E4*). The operator must specify the following for each array:

- The name of the array (same as the filename of the array config file)
- The number of gratings on the array (size)
- Whether to begin interrogating at the grating with the lowest or highest wavelength

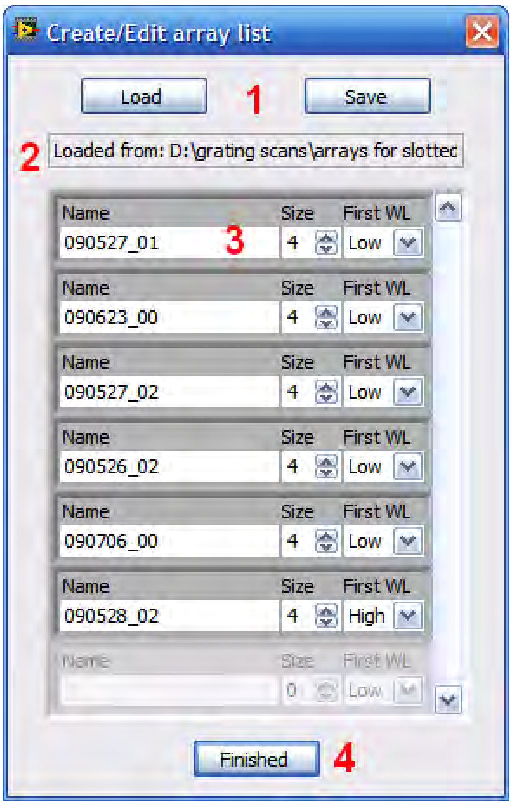


Figure E5: *Array list editor*

1. Load or save an array list.
2. Status/location of current array list.
3. Click to edit an existing entry, double-click & begin typing to create a new entry.
4. Click to return to array list selector (*Figure E4*).

E.3.3 Full-Automatic Mode Controls

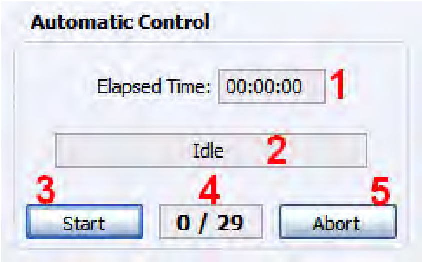


Figure E6: *Automatic mode controls*

1. Indicates time elapsed on automatic run.
2. Indicates status of automatic control program.
3. Click this button to start / pause / resume the current control program.
4. Indicates the currently selected FBG sensor and the total number of FBGs.
5. Click to exit automatic control mode.

E.3.4 Semi-Automatic Mode Controls

Figure E7: *Semi-Automatic mode controls*

Controls in semi-automatic mode are much the same as full-automatic mode except that the operator must press the “Next >>” button to advance to the next sensor.

E.3.5 Overview

This figure shows the automatic control mode running. All normal user controls are disabled except for those to pause or abort the control program.

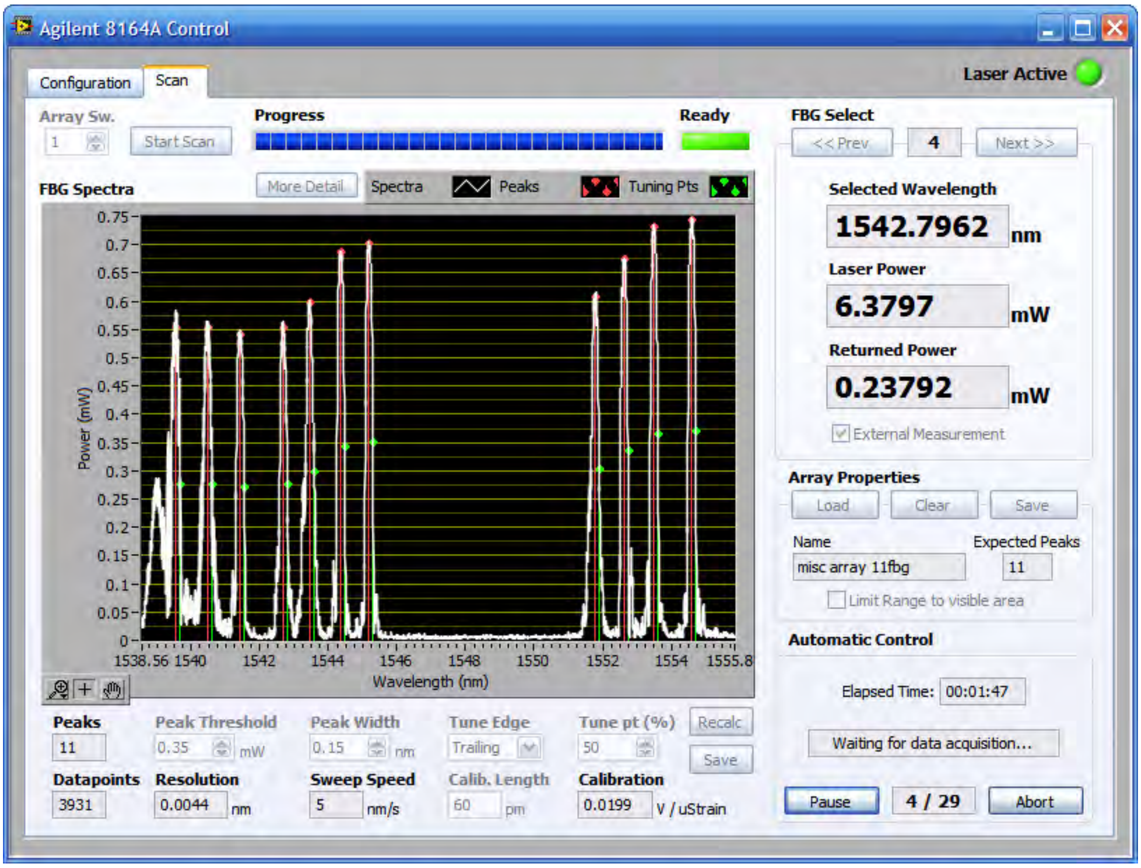


Figure E8: *Auto mode running*

E.4 Other Notes

- The external trigger requires the presence of a parallel port on the PC — all data pins on the port are briefly driven high when a trigger occurs.
- The program will function without the second (array selector) switch-box, however only one array can be used at a time.
- Names in an array list must be matched exactly to the names of the saved configurations; also the array sizes (sensors/array) specified in the list must match the number of peaks stored in the corresponding configurations.
- Scans will occasionally fail with a wavelength mismatch error. The cause for this is unknown however selecting a slightly different wavelength range, or changing the resolution, or sometimes just scanning again without changing anything usually resolves the issue.
- The 'Pause' and 'Abort' buttons for automatic control may become unresponsive while the program is waiting for devices or waiting for data acquisition.

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Optical Fibre, Bragg Grating , Structural Health Monitoring

19. ABSTRACT

The Structural Irregularity and Damage Evaluation Routine (SIDER) is a broadband vibration-based technique that uses features in the complex curvature operating shapes of vibrating structures to locate damage and other areas with structural stiffness variations. Historically SIDER has determined these shapes using out-of-plane acceleration measurements, however it may also be possible to determine these complex curvature operating shapes by using arrays of fibre Bragg gratings to measure the dynamic strain profile of the vibrating structure. This report outlines a review of commercially available FBG demodulation systems with the requirements of SIDER in mind. Three commercially available systems were assessed in the Laboratory and found to be unsuitable for this study. Hence in order to achieve a suitable outcome a purpose-built demodulation system was developed by DSTO. This report describes the assessment of the commercial systems as well as the development and evaluation of the DSTO purpose-built demodulation system.